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Mirror Neurons: Origin, Past and Current Research Techniques, and Possible Functions

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Abstract

In the early 1900s, mirror neurons (MNs) were discovered accidentally while performing experiments in the F5 brain area of monkeys. The neuroscientist Giacomo Rizzolatti and his colleagues were first to define MNs, which were located in the ventral premotor area F5 of macaque monkeys(Kilner and Lemon 2013). Following MN discovery in monkeys, scientists proposed the existence of MNs in humans. Since then, numerous studies have been conducted to support their existence in humans. MNs are structurally similar to other neurons, however their unique feature is the ability to fire action potentials, not only when a subject is performing an action, but also when the subject is observing the same action performed by an experimenter (Cook et al. 2014). Over the years, through different studies, scientists have proposed the origin and functions of MNs. In this review, I present the different methods used to study MNs and their hypothesized functions. Most studies done in humans are based on functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). However, considering the nature of these methods, it is difficult to derive conclusive evidence on the functions of MNs.

Introduction

Prior to the discovery of MNs, experiments using electron encephalogram (EEG), done by French scientists, showed evidence of a MN-like system. These scientists observed suppression in the electrical activity (mu rhythm) over the bilateral sensorimotor cortices when a person's hand was moved and 50% suppression when the person simply watched another person's hand moving (Gastaut and Bert 1954). Prior to defining MNs as such, Rizzolatti and colleagues studied how the activity of neurons in the F5 region of macaque premotor cortex correlates with variety of simple motor acts, such as reaching or grasping. To their surprise, they discovered that a great number of F5 neurons were active during the experimenter's actions and in the absence of the monkey's actions (di Pellegrino et al. 1992). After discovering the unique characteristic of F5 neurons, scientists conducted an experiment in which neurons were recorded using tungsten microelectrodes and examined by performing a series of grasping actions in front of the macaque monkey. The monkey's behavior and the experimenter's actions were recorded on one track of a video tape and the neural activity was recorded, simultaneously on a second track of the same tape. After analysis of the recordings, scientists reported that F5 neurons were triggered by the experimenter's movements. They also noticed that the monkey's responses were stronger when the observed stimuli were closer to the subject (di Pellegrino et al. 1992).

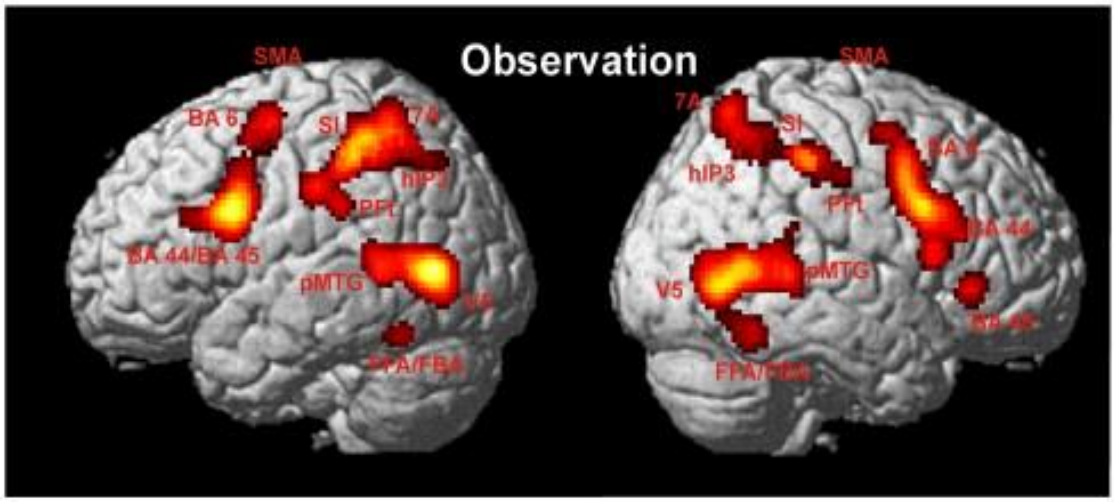
Early studies in monkeys revealed 3 types of MNs. The first type was named "strictly congruent MNs", which are known to discharge during observation and execution of the same action. The second type, "broadly congruent" MNs are active during the execution of one action and also during the observation of one or more similar, but not identical actions. The third type, known as "logically related", respond to actions of different goals. (Lingnau and Caramazza 2014). Fewer studies provide direct evidence for the existence of MNs in humans; however, there is data from neuroimaging, transcranial magnetic stimulation (TMS), and behavioral studies suggesting their existence in humans. Functional magnetic resonance (fMRI) has been a useful tool in identifying brain regions that are active during observation and execution. In another group of studies done in humans, "mirror" motor evoked potentials (MEPs) suggest a human mirror mechanism. Specifically, it has been shown that when applying TMS during passive action observation, the amplitude of MEPs recorded from the muscles, required to execute that action, was greater compared to the amplitude of the MEPs recorded when observing a different action. Another evidence of a human mirror mechanism is automatic action. Automatic action occurs when observation of an action involuntarily facilitates the performance of a similar action that requires the use of the same body parts (Lingnau and Caramazza 2014).

Scientists have proposed 2 accounts of MNs known as the genetic and associative accounts. The genetic account holds gene-based natural selection to be responsible for the MNs in humans. On the other hand, the associative hypothesis suggests that MNs are a product of general processes of associative learning (Cook et al. 2014). Scientists have discovered that associative learning depends on contiguity and contingency. According to the associative account, MNs acquire sensorimotor matching properties only when an individual experiences contingency between sensory events and performed actions. Researchers have established that contingencies can be experienced between both low and high-level sensory and motor

representations (Lingnau and Caramazza 2014). According to Cook *et al*, MNs could have acquired their properties through sensorimotor associative learning. The same scientists argue that this type of learning occurs when there is a correlation between the excitation of sensory and motor neurons (Cook et al. 2014). According to the associative hypothesis, the properties of MNs evolve by developing a system that receives correlated experience of observing and executing similar actions. When the system receives such correlated experience, it produces logically related MNs (Cook et al. 2014).

Scientists suggest that MNs are present in more than one area of the brain. In humans, MNs can be found in posterior regions of the inferior frontal gyrus, inferior parietal cortex, dorsal posteromedial cortex (PMC), superior parietal lobule, cerebellum, etc (Lingnau and Caramazza 2014).

Figure 1



Regions of the brain showing activation during action observation experiments. The image was obtained from a meta-analysis of the BrainMap database, fMRI, and PET literature on MNs, imitation, and action observation (Caspers et al. 2010)

Methods used to study MNs

Electroencephalograph (EEG) Study

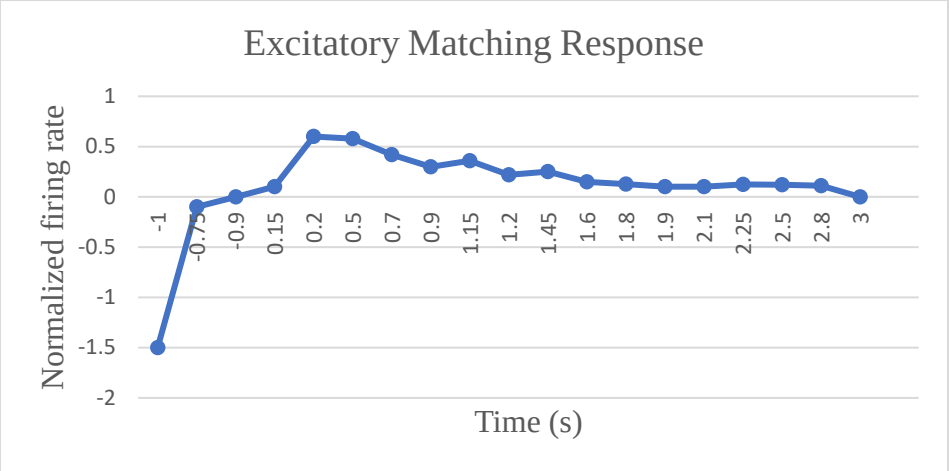
Following the discovery of MNs in macaque monkeys, a significant amount of research has been done to find the evidence of MNs in humans. However, most available data is best on fMRI, PET, EEG and TMS studies. In one of the studies, recording of neuronal activity was obtained, by a group of scientists, in 21 human subjects. The subjects were patients suffering from pharmacologically intractable epilepsy; therefore, intracranial depth EEG electrodes were implanted to identify seizure foci for potential surgical treatment. Both extracellular single and

multiunit activities were recorded. The study was broken in 3 components: facial expressions, grasping, and control experiments. For all 3 experiments, patients were presented with stimuli in the form of an image, a video, or cue word on a laptop. The grasping and facial expressions experiments involved 2 conditions: action-observation and action-execution. In the grasping experiment, the action-observation condition involved a short video depicting a specific action. In the facial expressions experiment, the action-observation condition consisted of an image of a specific facial expression. For both facial expressions and grasping experiments, the action-execution condition was in the form of a cue word, presented on a laptop screen, of the action to be performed. The control component of the study was set up the same way as the other components; however, in the control, the subjects had to read the word and refrain from performing the action.

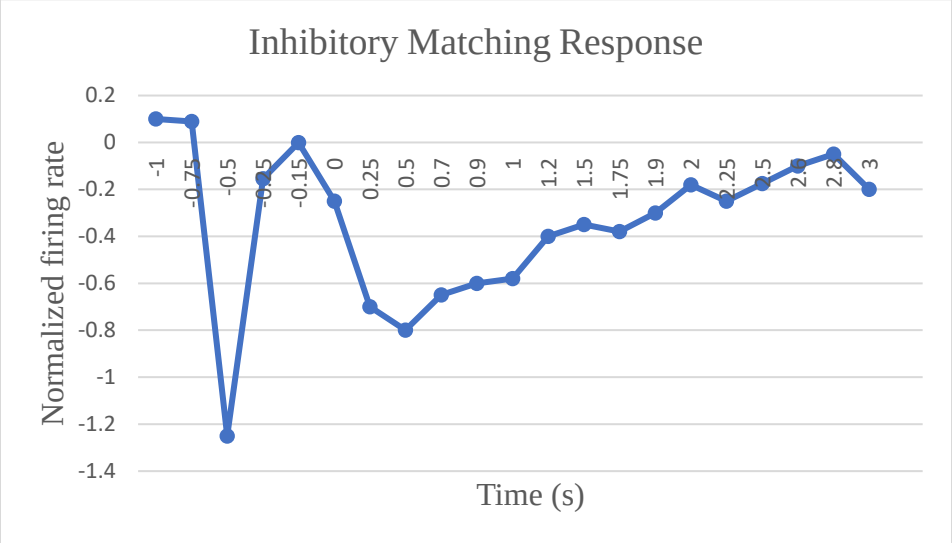
Neurons were recorded in different brain regions as subjects were performing tasks related to different components of the study. Regions of the brain where neurons were recorded include the medial frontal cortex and medial temporal lobe. A 2 tailed paired t test was used to test significant changes in the firing rate during baseline and after stimulus onset. The neutral response during action observation and action-execution was examined for each action. Each cell was then classified based on the condition in which it was responsive. After classifying cells, only the action observation/execution matching cells were analyzed. a chi-square test and a Fisher's exact test were performed on the proportion of cells in brain regions where neurons were recorded. These tests were done to find whether the proportion of action observation/execution matching neurons was significantly higher compared to what is expected by chance. Moving forward, scientists only analyzed anatomical regions with a significant proportion of action observation/execution matching neurons. Such brain regions include the supplementary motor area (SMA), Para-hippocampal gyrus, hippocampus, and entorhinal cortex (Mukamel et al. 2010).

Most observation/execution matching neurons were classified as single units. The temporal profiles of neural activity were examined by computing the average response profile of all action observation/execution matching neurons. Examination of temporal files was performed for cells exhibiting excitation to both conditions (action-observation and action-execution), inhibition to both conditions, and cells exhibiting excitation during action-execution and inhibition during action-observation. Responses were normalized to range between 0 and +1, for each excitatory response, and 0 to -1 for inhibitory responses. According to Mukamel *et al*, data suggests "mirroring spiking activity during action-execution and action-observation in human medial frontal cortex and human medial temporal cortex"(Mukamel et al. 2010). Based on their data, Mukamel *et al*, also suggest "the existence of multiple systems in the human brain endowed with neural mirroring mechanisms for flexible integration and differentiation of the perceptual and motor aspects of actions performed by self and others" (Mukamel et al. 2010).

Graph 1



Graph 2



Graphs 1 and 2 illustrate how fast excitatory cells reach their pick firing rate and how fast inhibitory cells return to baseline. These graphs were updated from original graphs published by Mukamel *et al*. For analysis purposes, each excitatory response was normalized to range between 0 and +1 and each inhibitory response to range between 0 and -1. Although it is difficult to deduce from the graphs, Mukamel et al noticed that excitatory cells reached peak firing rate faster during action-observation compared with action-execution and inhibitory cells returned to baseline faster during action-observation (Mukamel et al. 2010).

fMRI Adaptation

While fMRI is a good technique for neuroimaging studies, James Kilner and colleagues suggested an additional tool to be used in combination with fMRI. According to Kilner *et al*, evidence for MNs, especially in the inferior frontal gyrus (IFG) is based on the "demonstration that there is a significant spatial overlap between activity in this region during both action observation and execution"(Kilner et al. 2009). However, the evidence, according to experts in the field, is not reliable due to the inability to distinguish the types of neurons active during either action execution and observation. Based on these critics, Kilner *et al*, suggested adaptation or repetition suppression as a solution to attribute the fMRI response to a single neuronal population. fMRI adaptation is based on the fact that "neurons decrease their firing rate with repeated presentations of the stimulus, a feature that those neurons encode; this phenomenon is known as cross-modal repetition suppression (xmRS)"(Kilner and Lemon 2013). The experiment done by Kilner *et al* involved 10 healthy right-handed subjects. The subjects were asked to perform one of the 2 actions chosen to minimize artifacts in the fMRI data. Neuronal discharge, in the F5 of the monkey's brain has been shown to be modulated by the nature of the actions chosen. After recording and analysis of the data, Kilner *et al* claimed to have demonstrated "significant xmRS effects both when an observed action was followed by an executed action and vice versa" (Kilner et al. 2009). They also claimed that the results are in consistent with the existence of MNs in the human IFG, which is the homolog of area F5 in monkeys.

Brain lesion technique

Based on common techniques used to study MNs in humans, it is difficult to derive a conclusive evidence supporting their existence in humans. Brain imaging studies, such as fMRI and PET, only show activation of brain regions during specific tasks. In 2012, a brain lesion study was conducted to find whether lesions of certain sensorimotor regions would have an impact on the comprehension of stimuli associated with the use of the mouth, foot, and hand. Out of the 37 subjects, who participated in the study, 27 were patients suffering from a stroke on the left hemisphere, and the rest were healthy control participants. All participants were right-handed, native English speakers, and had no history of psychiatric or neurologic disorders. Patients had lesions in different locations within the left hemisphere. A total of 4 Brodmann areas were recorded in the study.

Like the EEG study, pictures were presented to participants accompanied with aurally words, which either matched or did not match the picture. Participants viewed pictures twice; the first time, the picture was accompanied by the matching word (congruent trial) and the second time the picture was accompanied by a non-matching word (catch trial). For the catch trial, each sound was carefully matched to the following parameters: target picture for body part (or neutral status), grammatical class, frequency, objective visual complexity and difficulty. Participants were then asked to press the space bar only when the picture/word pairs matched. Picture and word stimuli were 2-dimensional line drawings and corresponding recorded words, respectively. A total of 112-line drawings were used, and 64 of the items were actions/objects associated with

one of the 3 body parts (i.e. hand, mouth, and foot). 48 items were neutral, meaning that they were not associated with the use of a body part. Each set of neutral items was equated to an effector-specific set depending on these variables: word frequency, objective visual complexity, grammatical class, and item difficulty. Although, participants viewed a total of 112 stimuli items, analyses only included direct comparisons between carefully-matched subsets of items with equal numbers of items in each set (e.g. Hand versus Hand neutral etc.).

After collection of raw data, different analyses were conducted. The first analysis revealed that lesions in a range of key areas, previously associated with the putative humans MNs, can lead to a deficit for understanding foot-related concepts. Scientists also suggested an interaction between motor networks and the language network in humans which, according to them, do not seem to be confined to a specific region of the premotor/motor cortex. In contrast, motor-language areas appear to be spread over a range of different cortical regions. They also concluded that damage to certain regions of the language-motor network will result in lower relative accuracy on some effector-associated stimuli instead of completely blocking patients' ability to process motor-associated concepts. One limitation to the study is the inability to establish the determining factor in the degree of engagement of motor regions. Researchers could not establish whether the degree of engagement of motor regions reflect basic semantic processing in and of itself or whether it is due to some post-comprehension cognitive operations, such as motor imagery (Arévalo et al. 2012).

Possible Functions

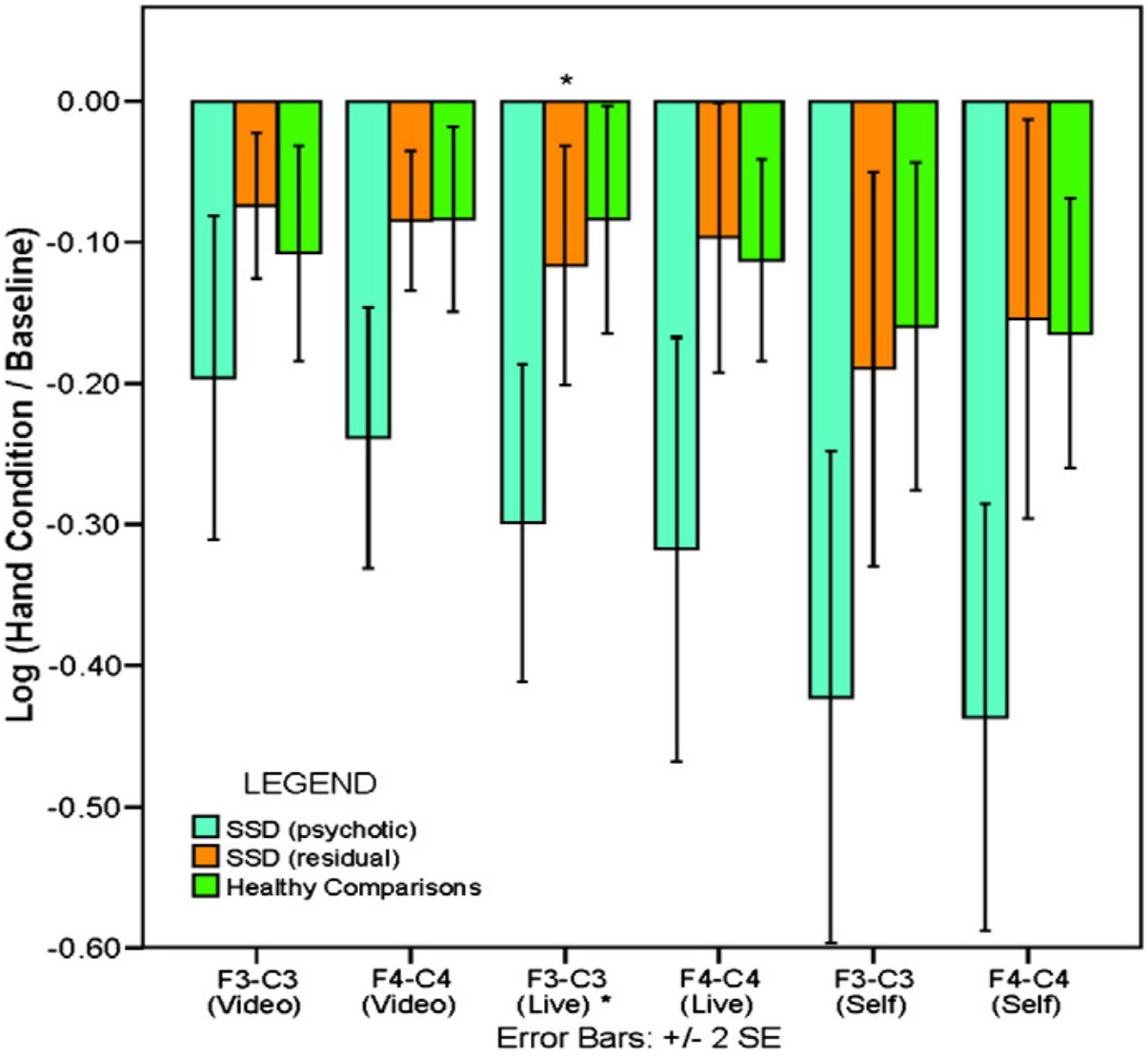
MNs in schizophrenia and autism

In the past, studies and experiments on social cognition in schizophrenia have been focused on the theory of mind, emotion processing, agency judgement, and empathy. Recently, stimulation theory has been proposed in the understanding of mental states. Stimulation theory is known to be a mechanism through which other people's sensory, motor, perceptual, and emotional experiences are experienced as if they were one's own. Scientists have proposed the mechanism for stimulation approach to be through MN system (McCormick et al. 2012).

Research show that patients with schizophrenia tend to display dysfunctional empathizing abilities. According to scientists, the dysfunction might be related to structural and functional deficits in the MN system and imitating network (McCormick et al. 2012). Observations suggest that emotional states are closely related to certain facial expressions. Scientists use a term known as emotional resonance to define a situation in which observation of an emotional state might result in a mirrored emotional state (Fahim et al. 2004). Studies of MN function in schizophrenia using neuroimaging methods suggest that people with schizophrenia show abnormal MN activity (McCormick et al. 2012). Scientists hypothesized that schizophrenia patients FA+ (patients with blunted or flat effects) would show relative decreased activity in the orbitofrontal, medial prefrontal, and anterior cingulate cortices (OMACC). In contrast, schizophrenia patients FA- were hypothesized to show significant activation of the same brain areas while passively viewing pictures with negative emotional content that requires neuronal activation of the OMACC. It was also suggested that the OMACC areas of the prefrontal cortex have a similar role in the MN

system (Fahim et al. 2004). In these studies, fMRI was used to detect relative changes of blood flow in the cortical areas in schizophrenia patients FA+ and FA- (Fahim et al. 2004). Collected data supported the hypothesis on the OMACC MN system role of representing emotions displayed in pictures (Fahim et al. 2004). According to Laurie McCormick et al, there is some overlap in the social cognition abnormalities between schizophrenia and autism and several studies show that patients with autism have reduced MN activity (McCormick et al. 2012). A research done to examine the differences in the suppression of EEG mu activity, which is a proxy for MN functioning, reported an increased left side mu suppression during observation of a hand movement in schizophrenia spectrum disorders (SSD) subjects in comparison to healthy subjects. According to McCormick *et al*, increase in the mu suppression may be indicative of increased MN activity (McCormick et al. 2012).

Graph 3



This graph shows that SSD subjects with active psychosis demonstrated significantly greater left-sided sensorimotor mu suppression during the observing live hand movement condition compared to SSD subjects with residual psychosis and healthy subjects. A mean log ratio less than zero indicates mu suppression (McCormick et al. 2012).

Hearing Sounds

According to Evelyne Kohler *et al*, it is possible for some object-related actions to be recognized by their sounds. It had been known, from previous experiments, that there are neurons that discharge both when a monkey performs and observes an action. However, scientists wanted to know whether there are neurons that also discharge when a monkey both performs a specific action and when it hears the corresponding action-related sounds (Kohler et al. 2002). Researchers used 3 awake macaque monkeys for the experiments. In these subjects, a total of 497 neurons were recorded, and these neurons were divided in 2 groups. In the first group of neurons, auditory properties were studied with sounds produced by the experimenter when a specific action was performed and when the action was absent. In the second group of neurons, digitized action-related sounds were used. Around 13% of the neurons recorded discharged both when the monkey performed a hand action and when it heard the action-related sound. After establishing the fact the neurons are also able to discharge both when the monkey performs an action and when it hears the corresponding action-related sound, researchers realized that some types of sounds were more effective than others (Kohler et al. 2002). The next step for researchers was to address the issue of neurons' capacity to differentiate actions based on auditory and visual characteristics. For the purposes of this experiment, scientists studied a specific set of neurons. The design of the experiment involved 2 hand actions that were randomly presented in vision-and-sound, sound-only, vision-only, and motor conditions (Kohler et al. 2002). Out of the total number of neurons tested, 88% showed auditory selectivity; and out 75% of these neurons showed vision selectivity for the same action. Scientists concluded that area F5 of the monkey brain contains audio-visual MNs that discharge when an action is executed, observed, and also when the action can only be heard (Kohler et al. 2002).

Action understanding

Previously, it was known that action understanding could have been achieved by matching or simulating observed actions in one's motor system. However, scientists have discovered that action understanding can be achieved by matching or simulating the goals of the actions instead (Hickok 2013). The urging quest was to know where the goals of an action are coded in the brain. The first step towards answering this question was to acknowledge that a goal is encoded as a sensory state. In a way to speak, "the motor system alone is blind" in the sense that it is incapable of understanding. According to scientists, the goals of an action are in the sensory consequences of actions. According to Rizzolatti *et al*, " the visual hypothesis implies that a description of motor events in visual terms is sufficient for action understanding (Rizzolatti et al.

2001). Neurons in the anterior superior temporal sulcus (STSa) have visual properties that support the visual hypothesis (Hickok 2013). These neurons are also able to relate perceived actions with sensory goals of the actions, which are the right properties for supporting action understanding. Experiments show that any disruption in the STS region caused by magnetic stimulation or degenerative brain disease disrupt the perception of action understanding (Hickok 2013).

When it comes to MNs, there are 3 alternatives to the action understanding perspective. The first one argues that "action execution and (self-)action perception co-occur and therefore become associated via sensory-motor learning in the response pattern of MNs" (Hickok 2013). The second one is the action selection model, which argues that "MNs code relations between perceived actions and possible action responses on the part of the observer" (Hickok 2013). This model was explained by scientists through relevancy of other people's actions to one's actions. This is a neural mechanism relating the perceived actions with appropriate response actions. This mechanism is supported by the presence of MNs are in a region that performs function for object-action interaction (Hickok 2013). The third alternative argues that "MNs are activated after an action is understood by other mechanisms as a means to make predictions about future actions" (Hickok 2013). Taking all evidence into consideration, scientists concluded that MNs do not contribute to action understanding, but rather reflect action understanding (Hickok 2013).

In their study, Kholer *et al* show that some of the neurons in the F5 area of monkeys respond to the vision and/or the sound stimuli of executed actions. These neurons are known as audiovisual MNs. Their findings left them with unanswered questions. One of these questions was to know whether audiovisual MNs participate in the ability of one to discriminate between actions independently of the modalities (vison, hearing, or execution) through which they are perceived and whether the firing of audiovisual MNs can discriminate between different actions in all modalities. Raw data from experiments were analyzed using a neurometric analysis known as the Receiver Operator Characteristics (ROC). However, results of the experiments conducted indicate that, "for half of the tested audiovisual MNs, the amplitude of the response does not differ significantly whether the preferred action is heard, seen or both heard and seen" (Keysers et al. 2003). Scientists discovered that audiovisual MNs had an interesting property of matching the sound and the vision of someone else's actions onto the monkey's own motor repertoire. Because of this property, scientists think that audiovisual MNs participate in the recognition of an action (Keysers et al. 2003).

Language

It has been proposed that the F5 area in the monkey's brain might be homologous to the Broca's area in the human brain (Gallese and Stamenov 2002). This idea has been supported by neuroimaging studies indicating the presence of MNs in or near the Broca's area. Because of this evidence, scientists have hypothesized that "MNs in pre-motor cortices may have played a pivotal role in the evolution of human language and communication" (Gallese and Stamenov 2002). Scientists have demonstrated an important role of the Broca's area and other parts of the

premotor cortex in the performance of working memory tasks, especially in the verbal domain (Gallese and Stamenov 2002). Neuroimaging studies done in the late 1900s, established the view that the premotor areas promote the verbal rehearsal mechanism. This mechanism with the phonological store, located in the left inferior parietal lobe, make up the " phonological loop" (Gallese and Stamenov 2002). Results from experiments done using fMRI suggest that " Broca's area and other premotor cortices constitute a sophisticated language system and a very efficient working memory mechanism" (Gallese and Stamenov 2002).

The mirror system hypothesis was developed based on the findings of the F5 area in the monkey's brain and its homologue, Broca's area, in the human brain. The mirror system hypothesis claims that a specific mirror system, responsible for grasping, evolved into a key component of the mechanisms that mature the human brain language (Arbib 2005). According to scientists, having a MN system should not considered as an equivalent for language development. It is evident that monkeys have a MN system, but they do not have a language. According to the same source, a MN system can be used in some other species for other social behaviors (Arbib 2005). The mirror system hypothesis also suggests that a mirror system for grasping is not in itself adequate for the copying of actions. Therefore, "further evolution of the brain was required for the mirror system for grasping to become an imitation system for grasping" (Arbib 2005). Scientists define protolanguage to be a system which serves as a precursor to human language. They also hypothesized a list of properties supporting protolanguage; one of them being complex imitation. Complex imitation was defined as " The ability to recognize another's performance as a set of familiar movements and then repeat them, but also recognize that such a performance combines novel actions that can be approximated by variants of actions already in the repertoire" (Arbib 2005). Symbolization is another property of protolanguage hypothesized by the same scientists. Symbolization was defined as the aptitude to associate symbols with a class of episodes, objects, or actions; it is likely that these symbols might have been based on manual and facial gestures rather than being vocalized (Arbib 2005). According to Michael Arbid, complex imitation has 2 parts: "the ability to perceive the possibility of a novel action to be approximated by a composite of known actions associated with appropriate sub-goals, and the ability to employ this perception to perform an approximation to the observed action, which may then be refined through practice" (Arbib 2008). Both parts, Arbid claims, are useful when the child is learning a language whereas the first one predominates in adult use of language because the focus shifts from knowing novel words and constructions to finding the appropriate way to continue a dialogue (Arbib 2008).

Visual system

Research shows that MNs indicate visual responses associated with other subjects' actions and moto-related activity during execution of the same grasping action (Maeda et al. 2014). A study was done to investigate the ability of neurons in inferior parietal lobule, including the anterior intraparietal area and PFG, of macaques to represent visual images of the monkey's own hand during a self-generated grasping action". Out of the total number of neurons related to hand manipulation tasks, 23% responded to video clips of the monkey's own hand action or to the experimenter's hand action. Out of these neurons, about half of them responded to video clips of

the monkey's own hand, even without an image of the target object; these neurons were named "hand-type". About 60% of the neurons that responded to video clips were defined as MNs and showed visual responses to the experimenter's action and motor responses. According to Kazutaka Maeda *et al*, "These results suggest that hand manipulation-related MNs in anterior intraparietal/PFG play a fundamental role in monitoring one's own body state based on visual feedback" (Maeda et al. 2014).

According to Ayse Saygin and Frederic Dick, in contrast to monkeys, "correlational and causal studies show that human MNs have been linked to the processing of point-light biological motion stimuli, which depict actions through motion cues". EEG and fMRI studies indicate that MNs can respond to stimuli that were non-existent in the natural environment until very recently, e.g. the 20th century point-light displays and 21st century Japanese androids. According to scientists, such evidence point to a more adaptationist account rather than a genetic account of MNs (Saygin and Dick 2014).

MNs and behavior

According to scientists, MNs can change the monkey's responses to affect its behavior. They take a stand on the relationship between understanding and behavior. Erhan Oztop *et al*, suggest that to benefit the organism, understanding must affect behavior (Oztop et al. 2013). When a monkey observes an action performed by another monkey, in response to the observed action, the monkey can simply change its behavior or can plan a set of actions to take.

Nightmare frequency

Other scientists have been investigating the relationship between nightmares and the MN system. According to these scientists, nightmares are symptoms of disorders, such as bipolar disorder, associated with anomalies in the MN system (Nielsen et al. 2013). Based on a factor analysis of the mirror behavior questionnaire (MBQ), there are 4 types of mirror behaviors that might be associated with nightmares: Empathy/Emotional Contagion, Behavioral Imitation, Sleepiness/Anger Contagion, and Motor Skill Imitation. A study to assess possible relationships between nightmares and mirror behaviors in a population of college students was conducted. A total number of 480 students participated in the study; about 45% of the students were males and 55% females. The study involved an extensive battery of questionnaires on personality and dreaming. A 16-item self-report scale was used assess mirror behaviors. This self-report scale contained items that represent empathy as well as contagious emotions, mirroring of body postures and speech patterns, imitative learning of motor skills, and contagious sleepiness, yawning, and anger. After analysis of the raw data, scientists concluded that the results provide preliminary evidence of the association between nightmare frequency and a tendency to express waking mirror behaviors. The results also support the notion "that a previously observed association between mirror behaviors and dream-enacting behaviors reflects a mirror neuron mechanism that underlies both waking mirror behaviors and nightmares" (Nielsen et al. 2013). Although the actual mechanisms that influence mirror behaviors and nightmares are unknown,

scientists propose mechanisms such as motor resonance and the central mirror neuron system to underlie the production of both mirror behaviors and dream content (Nielsen et al. 2013).

Imitative behaviors

It has been suggested that action perception and imitative behaviors are impaired in Autism Spectrum Disorders (ASDs). Studies have shown a correlation between affected brain regions in ASD patients with brain regions involved in decision making (Khalil et al. 2018). Among others, these brain regions include the amygdala, prefrontal cortex, superior temporal sulcus, and fusiform gyrus. Additional studies show that patients with ASD did not show autonomic arousal when completing different observation tasks, such as looking at a cap VS looking at a parent. Researchers were also able to observe a switch in decisions, regardless of the outcome, in ASD patients. This observation led the scientists, who conducted the experiments, to conclude that "participants with ASDs do not modulate their choice despite their understanding of the motivating purpose of the stimuli" (Khalil et al. 2018). Another experiment, using facial electromyography, indicated the failure to mimic facial expressions in ASD patients. Vitality form is defined as the appraisal of the action from the dynamics of the movement. Previous research reported severe deficits in recognizing vitality forms in ASD patients. As summarized here, there has been remarkable findings on the correlation between social decision and autism. Unfortunately, there is no current proof of a link between social decision making and the impairment of the MNs. Nevertheless, scientists assume neurophysiological interaction between the pathways responsible for the MNs imitative behavior, motor action, and social decision making. Scientists suggest future studies that will combine behavioral tasks with neuroimaging methods and transcranial brain stimulation as well as computational modeling to help validate their suggestion (Khalil et al. 2018).

Tool-use

In association to the ability to imitate, other scientists have been focusing on tool-use skills in humans and non-human primates. Scientists show interest in this topic because tools can be perceived as "extra limbs". Besides this perception, limbs such as hands can be objectified and as a set of tools (Iriki 2006). MNs can be classified in different types based on the mode of action that they modulate. For instance, some MNs discharge during empathy-like reactions while another group of MNs will discharge during sound recognition. Scientists suggest that tool-responding MNs increase monkeys' ability to understand the goal of tool-using actions by the experimenter (Iriki 2006).

Understanding one's intentions

It had been established that MNs play a significant role in action recognition/understanding. After analysis of what an action entails, scientists have realized that action recognition involves the recognition of the goal and the understanding of the agent's intentions. Intention could be described in 2 different ways as the following example illustrate. In the scenario where one reaches his/her hand towards an object, like a cup, the observer can simply recognize the person's intention of grabbing the object. Besides the simple intention of grabbing the object, the observer can also recognize the global intention or the goal of grabbing that object (e.g. does the

person wants to eat, throw, or break the object) (Hickok 2013). Past studies suggest two types of task-associated goals known as proximal and distal goals (Umiltà et al. 2008). In the action described above, the proximal goal will be grasping a cup, while the distal goal can be drinking out of the cup. Considering the suggested goals, scientists were intrigued to understand how a monkey subject can know whether the intended goal was achieved. Umiltà et al. suggest that a monkey subject can be able to determine the accomplishment of the intended goal with the aid of somatosensory perception through senses such as vision and touch (including texture). According to Hickok, the motor system is incapable of understanding; therefore, the goal (s) of an action is/are in the consequences of the action (s), and to understand an action, one must understand the sensory goals (Hickok 2013).

Discussion

The discovery of MNs is considered a breakthrough in neuroscience, mostly because of their unique properties. Because of their characteristics, MNs constitute an attractive topic for neurobehavioral studies. Since their discovery, a considerable amount of research has been done, both in monkeys and humans, to find evidence of hypothesized or suggested functions. Majority of the evidence reported in support of the existence of MNs in humans have been based on TMS, PET, EEG, and fMRI studies. Unfortunately, each of these techniques has limitations. A general pattern is the lack of ability to identify single neuron activity. The brain is a network of intertwined neurons, which are always active as they are involved in processing and transmitting information that support a variety of actions. Brain imaging techniques such as PET and fMRI can only reveal brain areas that are activated during tasks performed by subjects. normally, following collection of fMRI raw data, a series of steps are performed to reduce artifact and noise-related components (background noise). Following removal of "background" noise, the data can now undergo statistical analysis. Despite the careful analysis, brain imaging techniques are only limited to show correlation between certain actions/functions and areas of the brain that are activated.

An immediate concern with correlational data is the presence of more than one type of neurons in the activated brain regions. An earlier study done in monkeys showed that out of the electrically recorded neurons in the F5 region, only 17 % had the properties of MNs (Gallese et al. 1996). The presence of other types of neurons could potentially indicate that MNs are not the only neurons involve in hypothesized functions. One solution to this problem will be to conduct a brain lesion study. A brain lesion study conducted in 2012 to investigate the impact on the ability to comprehend certain stimuli upon lesions of sensorimotor regions showed that lesions in brain regions associated with human MNs can lead to impairment in the understanding of foot-related concepts. Such brain lesion studies as the one described above, can only prove that brain regions associated with MNs are involved in the hypothesized functions. Brain lesion studies cannot prove that MNs are solely responsible for the actions/functions claimed by scientists. A more convenient solution would be to use animal models which will allow for precise manipulation of neural networks. For a long time, a complex task such as empathy was only thought to be present in species with well-developed cortical circuits. However, over the years,

scientists have discovered that rodents can show empathy, a task that has been associated with MNs. Other than rodents, scientists have proposed the use of marmosets and songbirds in the understanding of the MN system. Other than a better understanding of the mirror mechanism, scientists also suggest that information obtained from studies with better animal models can contribute to the development of new therapies to treat psychiatric disorders such as autism (Ferrari and Rizzolatti 2014). It is possible for empathy to rely solely on MNs, a combination of MNs and accompanying neurons, or a different type of neurons. To know the exact types of neurons involved in empathy, techniques allowing single-cell resolution and manipulation need to be used (Meyza et al. 2017).

Conclusion

The discovery of MNs in macaque monkeys was a breakthrough in neuroscience. In this paper, I have defined MNs, discussed proposed origin accounts, described common techniques used in studying MNs, and presented some of the hypothesized functions of MNs. The fact that majority of the current data supporting existence of MNs in humans and their functions is not conclusive, does not dismiss findings from these studies. Instead, these findings should be used as background information for further studies on a neurochemical and molecular level.

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